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2004 RRR for FNAL-SRF Measurement Report

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1 INTRODUCTION

The evaluation of purity and thermal conductivity of the Niobium to be used in the fabrication of superconducting RF cavities at liquid Helium temperatures is normally done by measuring the Residual Resistivity Ratio (RRR) of a sample of the material. The RRR is the ratio between the resistances of the sample at room temperature and 4.2 K, close to the operating temperature of the cavity. It is well known that the thermal conductivity of pure metals is strongly correlated with the RRR parameter.

Fermilab is involved in the fabrication of transverse deflecting and third harmonic superconducting RF cavities. Both cavity types are fabricated with the technology developed for the TESLA linear collider, that is through deep drawing of ~3 mm thick Niobium sheets. They are operated at 1.8 K and 3.9 GHz. Unlike the 3rd harmonic cavities, which are operated in the accelerating mode, the CKM cavities are designed for a transverse deflecting mode.

The RRR plays a particularly important role in these cavities because it correlates with the thermal conductivity of the cavity wall. The heat deposited due to RF heating on the inside surface of the cavity needs to be conducted through the cavity wall to the superfluid helium bath on the outside of the cavity. The exponential dependence of the RF surface resistance in the niobium on temperature results in thermal runaway (thermal quench) if the heat is not evacuated efficiently. It is therefore crucial that the thermal conductivity and the RRR parameter be as high as possible.

In order to allow measurement of larger quantities of samples during one cool-down a sample-holder for twelve samples was fabricated. This sample-holder can be inserted into an existing temperature sensor calibration test facility at Fermilab's Technical Division superconducting materials development lab. This test station features a 25 cm high, 6 cm diameter sample volume in which ambient to 2K temperatures can be provided. The temperature control is obtained with the following process. The sample volume is contained within a cylinder, which in turn is contained in a cylinder filled with liquid helium. The inner cylinder with the samples is thermally insulated from the helium bath via the evacuated gap between the helium vessel and the sample vessel. Liquid helium can be pumped into the sample vessel from the helium vessel. Heaters are used to evaporate the helium in the sample vessel. Thermal equilibrium is achieved through regulation of the heater power in conjunction with the amount of liquid or gas injected into the sample volume. With this technique the temperatures in the test volume can be stabilized at the mK level. Convection in the gas is a major factor in the temperature regulation.

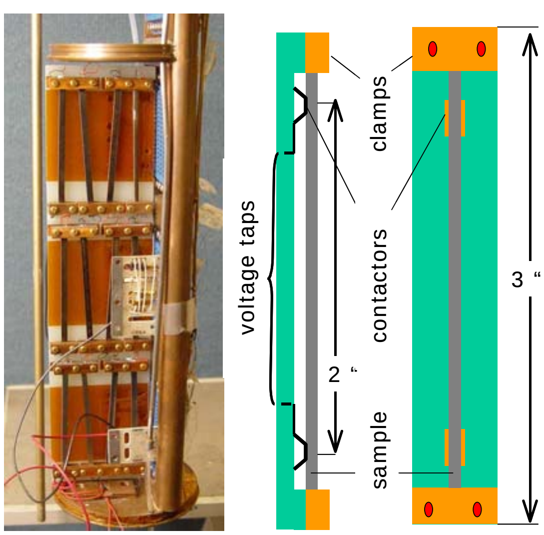

Figure 1a: Sample-holder with samples for RRR measurements.

Figure 2a: Cryostat for RRR measurements.

The temperature in the sample volume is measured with calibrated Cernox temperature sensors. Fig. 1 shows the sample-holder, which consists of a G10 plate to which the samples are affixed with Cu clamps and brass screws. The clamps also conduct the current to the samples. All samples are supplied with the 100 mA measurement current in series. The voltage is recorded from voltage taps, which consist of flexible Cu blades underneath the sample (see schematic in Fig. 2) placed ~5 mm inwards from the clamps such as to minimize current distribution effects. Wires are soldered to the flexible Cu contactors and routed to the edge of the G10 plate where they are soldered to conducting strips that are positioned such as to connect to the proper channels when the G10 plate is inserted into the spring-connector slot.

The samples are cut from the as received raw blanks with wire EDM. A study performed at DESY showed that the electro-erosion technique introduces hydrogen into the bulk and oxygen into the surface of the sample. According to the DESY measurements, however, this contamination is small enough to not cause any noticeably change of the RRR[2]. This is mostly related to the fact that RRR probes mostly the bulk property of the sample. Milling or water cutting was found to introduce less contamination. We chose the electro-erosion technique because it is the most convenient for producing small samples.

The data-acquisition is performed through a Labview data acquisition program. Measurements of the sample resistance are typically performed between 9 K and 10 K in steps of ~300 mK as well at some select temperatures up to room temperature. Repeated measurements were performed on select samples to estimate the measurement reproducibility of the Fermilab test station. The reproducibility was found to be ±5%. The RRR as defined in this document is the ratio of the resistances at room temperature and ~10 K (just above the super- to normal-conducting transition). The more rigorous definition of RRR used elsewhere[3] involves the measurement of the sample resistivity down to 4.2 K with magnetic fields above B_{c2} to suppress superconductivity. The (linear) extrapolation of the resistivity at 4.2 K to zero magnetic field, supposedly removes the magneto-resistance contribution and thus allows determination of the normal state resistivity at 4.2 K. This is the number then used as the low temperature value for the RRR computation. This more rigorous technique yields RRR values, which are between 5-10% higher than those calculated from the method we used here. This issue will be discussed in more detail in section 2.) on the basis of real measurement data.

[2] W. Singer, personal communication

[3] R. Goodrich et al., "Measuring Residual Resistivity Ratio of High Purity Nb", presented at the ICMC 2003, Anchorage, USA, Advances in Cryogenic Engineering, Vol. 49-50

2 BENCHMARKING WITH UW

A series of samples were measured at Fermilab and the Applied Superconductivity Center of the University of Wisconsin[4] in order to benchmark the measurement systems. **Table 1** summarizes those measurements. Note that the RRR definitions vary between the two institutions. The FNAL measurements are obtained from the ratio of room temperature and ~10 K resistance measurements at zero magnetic field. The UW definition of RRR on the other hand is the ratio of a 273 K and a 4.2 K measurement, where the 4.2 K measurement is extrapolated to zero magnetic field from the measurements at several magnetic fields above critical. In the second column the FNAL data were therefore corrected and based on the same definition as the UW data.

The correction used for at the high temperature end, between 300 K and 273 K was obtained with equ. (1) as published in [5], where the room temperature needs to be given in °C and l/A is the ratio of distance between voltage taps on the sample over cross-sectional area. Typical l/A factors for our sample geometry are 10^4.

$$R_{273} = R_{RT} + 4.54 \cdot 10^{-10} \cdot (l/A) \cdot (0 - T_{RT})$$

The correction at the low temperature end was obtained from extrapolation of the 9-11 K resistivity measurement points to 4.2 K. A typical, linear extrapolation to low temperature for the three samples discussed here is:

$$R_{4.2K,0T} = (1.3 \cdot 10^{-12} \cdot 4.2 + 3 \cdot 10^{-10}) \cdot (l/A)$$

Note that the extrapolation procedure to low temperature is using a linear extrapolation based on very few measurement points. Also the uncertainty in *l/A* (measured "by hand") is considerable given that the samples do not have a perfect rectangular cross-section. Despite the fact that the data conversion procedure for FNAL data is rough, the agreement between the ASC/UW and FNAL data on the benchmarking samples is reasonable.

Table 1: Benchmark measurements of several samples between UW and FNAL. *Measured RRR defined as R(RT)/R(10K,0T) was extrapolated to R(273K)/R(4.2K,0T) to agree with ASC/UW RRR definition.

	FNAL	FNAL*	ASC/UW
A1	415	442	429
A2	400	449	440

[4] Courtesy of A. Squitieri, ASC / UW, April 2004
[5] M. Kuchnir, "Apparatus for measuring RRR", Fermilab Technical Memo, TM-2201, Jan. 2003

3 MATERIAL ACCEPTANCE TEST

A new batch of high purity Niobium was ordered from Wah-Chang during 2003 for the transverse deflecting and 3rd harmonic cavity projects. The new transverse deflecting cavity material was chosen to be thicker, ~ 2mm, to strengthen the cavities mechanically. The 3rd harmonic material thickness was chosen as ~3 mm. The following discusses the results of RRR measurements obtained on a series of samples of as received material. To measure the effect of the various treatment steps inflicted on the Niobium blanks in the course of the cavity manufacturing, the RRR samples underwent through a full sequence of treatment steps, as listed in **Table 2**. The results of the RRR measurements on these samples is shown in **Figure 3**. The figure clearly shows that within the measurement reproducibility of ±5% there is no discernible effect of the surface treatment on the RRR. This essentially tells us that these treatment steps only affect the properties of a the surface layer and not the bulk.

Note that the samples 1-3 of the 3rd harmonic batch were sent to ASC/UW for a comparative measurement following the test at Fermilab. Appendix A gives the experimental data in detail. The result obtained after treatment on the 6th sample was removed from the chart because of large (unexplained) variations in the 10 K resistance between subsequent measurements (see Table 10). Data are discussed in detail in appendix A.

Table 2: Sample surface treatment procedure.

Step	Comment
de-greasing	ultra-sound in ultra-pure water, rinsing until water R>18 MΩ
strong etch	100 min etch in 1:1:2 BCP removing ~100 μm, followed by rinse until R>18 MΩ
bake	bake in UHV (P<1μTorr) at 800 C for 5 hrs
light etch	20 min etch in 1:1:2 BCP removing ~20 μm, followed by rinse until R>18 MΩ

Table 3: RRR of 3rd harmonic (A1-A6) - batch 1 and CKM (=transverse delfecting) (C1-C6) 2-mm batch samples as received and after surface preparation.

sample	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**
RRR (before treatment)	427.5	417.1	414.4	416.5	420.5	413.2
RRR (after treatment)	414.2	399.5	398.6	379.8	424.7	**(500)**
sample	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
RRR (before treatment)	460.0	445.3	376.3	425.9	428.6	453.8
RRR (after treatment)	409.2	413.2	428.3	417.2	420.9	417.2

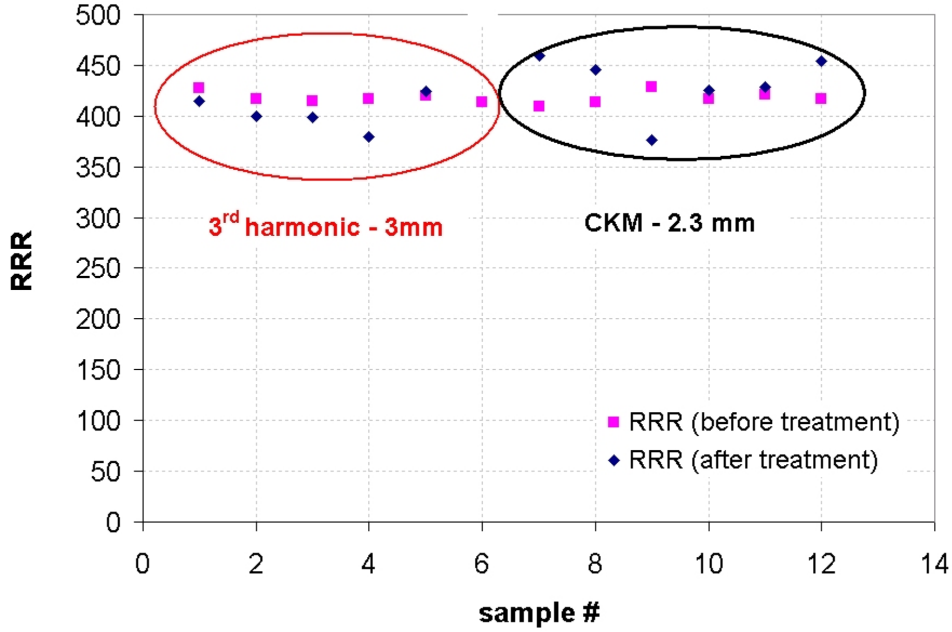

Figure 3: RRR test results on niobium for the FNAL third harmonic and transverse deflecting (CKM) cavities, as received and after a complete standard treatment for cavities, that includes several cleaning, rinsing and etching steps and a high temperature anneal.

The as received material satisfies the RRR specification for the 3rd harmonic and CKM cavities.

4 WELD-SERIES 1&2

Two weld tests were performed with 3rd harmonic batch 1 material. For that purpose plates were cut from raw blanks. Some samples were cut from the raw blanks with wire EDM. Then the plates were degreased (rinsing in ultra-sonic bath) and lightly etched. A special welding fixture was built (**Figure 4**). The to-be-welded plates are clamped between bolted aluminum plates. The fixture not only holds the pieces together, but also drains heat during the welding. The welding was performed at Sciaky Inc. / Chicago (weld-parameters?). The pressure in the e-beam welding chamber was $\sim 4\times10^{-6}$ Torr.

Finally the welded plates were cut with wire EDM into ~0.1" wide and 3" long sticks as required for the RRR measurements (**Figure 5**) and submitted to a RRR measurement. The weld typically is ~5 mm wide and therefore covers at least two samples.

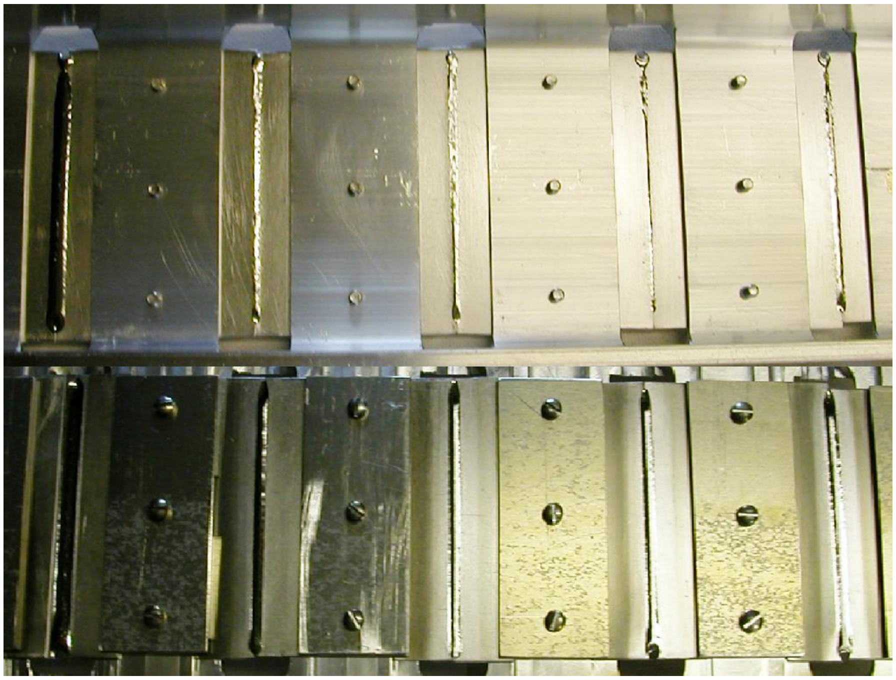

Figure 4: Welding test fixture top and bottom after welding. The samples plates are clamped between aluminum plates

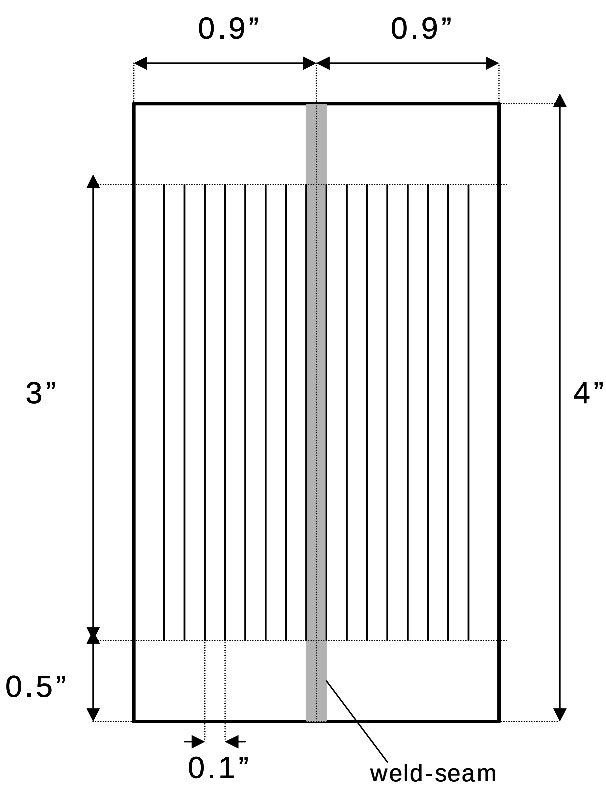

Figure 5: Schematic of how weld-samples were cut from welded plates

The RRR data are summarized in **Table 5** and **Table 6**. **Table 4** shows the RRR measured on four samples cut from the edges of the plates (two samples from each edge), from which weld-sample 1 was made. **Table 5** gives the RRR data of sample 1 and **Table 6** gives the measured RRR of sample 2. **Figure 6** shows the weld series measurements in terms of the position of the stick with respect to the weld. Each point represents the center of the ~2.5 mm wide samples. The exact dimensions of the samples can be found with the data in appendix B. The samples, which form part of the weld-seams, are clearly indicated in the tables.

The average RRR of the samples cut from the sheets before welding is 417. Note that this measurement result is consistent with the RRR measured on 6 other samples in the frame of the material acceptance test (Table 3). The RRR data obtained on the strips cut from the weld-samples are given in **Figure 6**. The weld-test data in **Figure 5** were normalized on the before-weld average to better represent the effect of welding. Detailed measurement data are given in appendix B.

Table 4: RRR of 3rd harmonic / batch 1 samples before welding.

sample	BW 1	BW 2	BW 3	BW 4
RRR	420	418	419	410

Table 5: RRR of 3rd harmonic / batch 1 weld-series 1 samples. *Data indicated are from a second measurement. Position refers to the distance of the sample center-line from weld center-line in mm. The samples representing the weld region are typed in red.

position (mm)	-17.4	-14.9	-12. 5	-10	-7.5	-5	-2.5
RRR	415	412	409	396*	390*	437	429
date measured	10/8/04	10/8/04	10/8/04	5/3/04	5/3/04	4/10/04	4/10/04
sample name	A1	A2	A3	A4	A5	A6	A7
position (mm)	**-1.2**	**1.25**	5	7.5	10	12.4	
RRR	**397**	**391.5979**	432	427	428	406	
date measured	**4/10/04**	**10/8/04**	4/10/04	4/10/04	4/10/04	10/8/04	
sample name	**A8 (weld)**	**weld**	A9	A10	A11	A12	

Table 6: RRR of 3rd harmonic / batch 1 weld-series 2 samples. Position refers to the distance of the sample center-line from weld center-line in mm. The samples representing the weld region are typed in red.

position (mm)	-17.9	-15.9	-13.7	-11.5	-9.3	-7.1	-4.9	**-2.5**	**0**
RRR	416	400	401	411	399	402	397	**435**	**443**
date measured	10/8/04	10/8/04	10/8/04	10/8/04	10/8/04	10/8/04	10/8/04	**5/3/04**	**5/3/04**
sample name	1B	2B	3B	4B	5B	6B	7B	**8B**	**0**
	weld							**weld**	**weld**
position (mm)	**2.5**	5	7.5	10	12.5	15	17.5	20	
RRR	**419**	413	425	427	427	444	420	433	
date measured	**5/3/04**	5/3/04	5/3/04	5/3/04	5/3/04	5/3/04	5/3/04	5/3/04	
sample name	**A2**	A3	A4	A5	A6	A7	A8	A9	

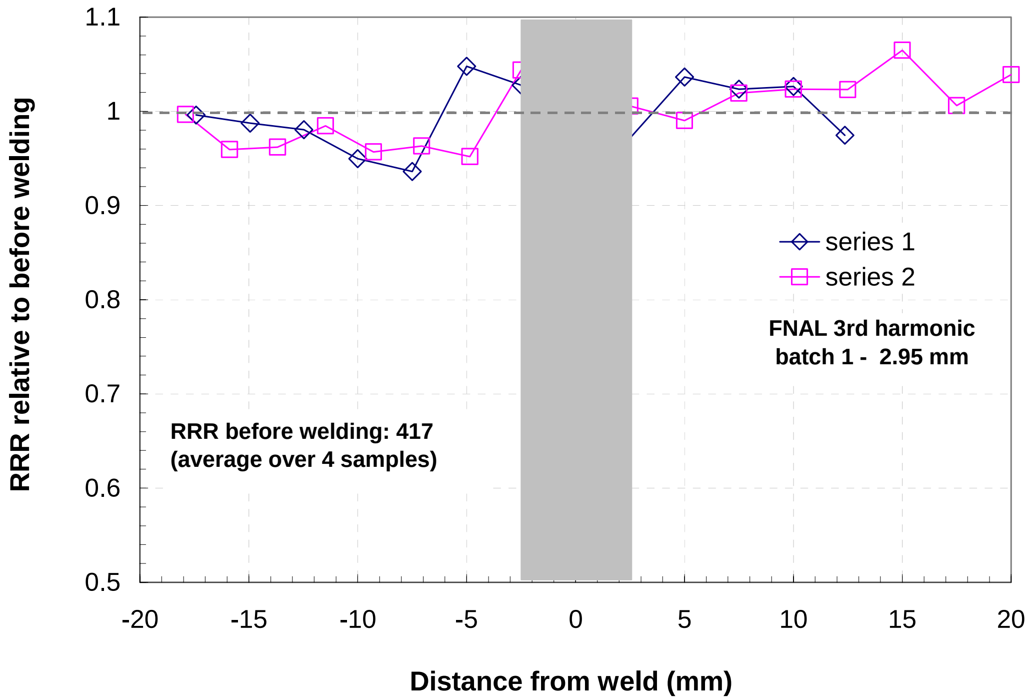

Figure 6: 3rd harmonic batch-1 weld series results (normalized to average RRR before welding, ~417). The gray strip in the center represents approximately the weld region.

The weld-series results show that the effect of welding on the RRR is minimal. Note that the RRR varies only within ±5%, which is more or less the measurement reproducibility of our 3R measurement system. In the case of weld-series 2 the RRR appears to increase slightly in the weld and slightly decrease close to the weld, which is similar to what was observed before at DESY[6]. The model developed at DESY is that gases evolving from the hot weld are re-adsorbed in the adjacent region, the so called heat affected region, which is hot enough to allow sufficient inwards diffusion and not hot enough to allow for substantial outward diffusion. The weld-series 1 sample, however, shows exactly the opposite behavior, which casts doubt whether the DESY model applies to the particular welds fabricated here. The lack of an effect of the weld on the RRR was also previously found in four weld-samples made at Sciaky with thinner material used for the first transverse deflecting cavities[7]. Another aspect of weld-sample 2, also observed previously in welds fabricated from thinner material, is that the RRR of the two discs welded together are slightly different (this is also reported in [5]). This could be the result of differences in RRR in the original sheet. Note that the relative RRR data shown in **Figure 6** were normalized to the same before welding value of 417 for both sides from the weld. This is actually the reason why the effect appears in this plot.

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[6] W. Singer et al., "RRR Degradation and Gas Absorption in the Electron Beam Welding Area of High Purity Niobium", p. 162 in Hydrogen in Materials and Vacuum Systems, G. Myneni and S. Chattopadhyay editors, AIP 2003;

[7] P. Bauer et al., "RRR Measurements on Niobium for Superconducting RF Cavities at Fermilab", Proceedings of the 11th RF Superconductivity Workshop, Luebeck Germany Sept. 2003;

5 EFFECT OF MEASUREMENT CURRENT ON RRR TEST

The measurements performed on 10/08/04 on samples of the 3rd harmonic batch 1 weld samples were performed not only at the usual measurement current of 0.1 A but also at 0.01 A. Differences in the results as obtained with the different currents are indicative of non uniform current distributions or heating effects, especially important at temperatures close to critical. As shown in Figure 7 the resistivity obtained from the measurements with two currents agree reasonably well. One can come to a similar conclusion for all other eleven samples as well (Figure 8). Closer inspection, however, shows that there is quite some difference between the results obtained from different current measurements at 9-10 K. Figure 9 clearly shows the large differences, very much in contrast to the difference at higher temperatures. The absolute difference is largest at low temperature and decreases exponentially toward larger temperatures. This together with the scattering of the differences to positive and negative signs with more or less equal frequency, made us believe that the issue was rather noise than systematic. Indeed, the separate analysis of the spread of 9-10 K data for the two different current settings showed the following. In the 0.01 A case the difference between one measurement and the average of all measurements in this temperature range, averaged over all samples is 25%, much larger than the similar value for the 0.1 A measurements. That indicates that the variations seen in Figure 9 originate to a large extent in the variation of the 0.01 A data themselves. With typical sample resistances of the order of μΩ, the voltage at 0.01 A becomes ~10 nV, hard against the resolution limit of the nano-voltmeter as well as close or even below the “noise” level in the system.

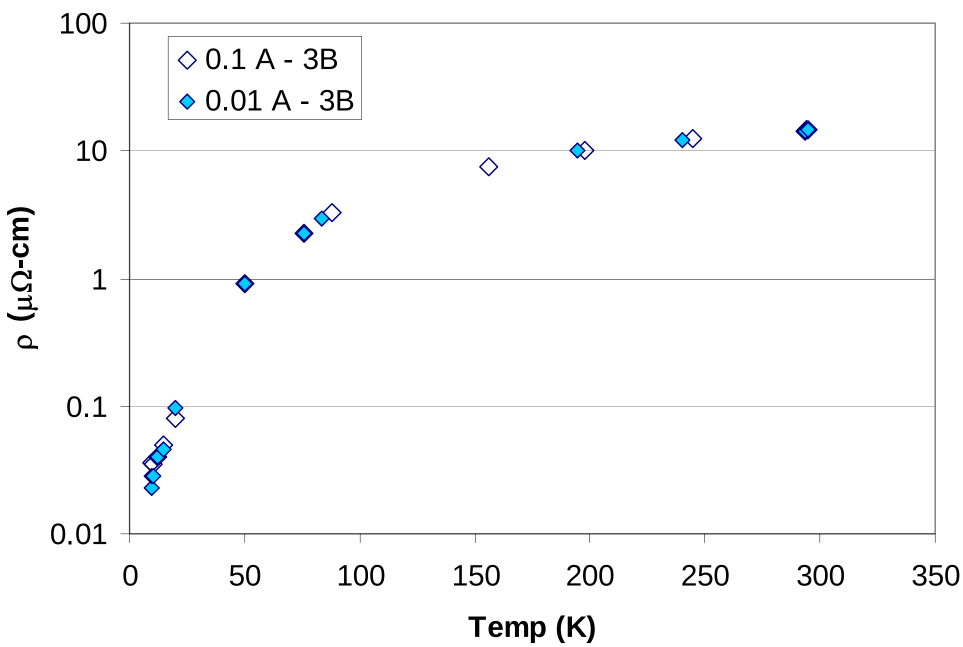

Figure 7: Electrical resistivity vs temperature as measured on 10/08/04 on sample 3B.

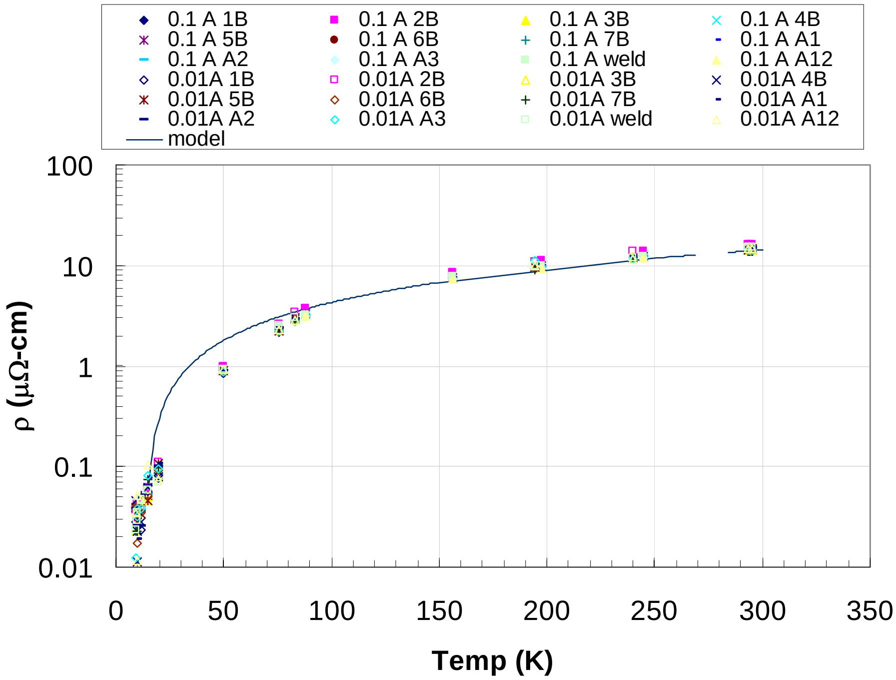

Figure 8: Electrical resistivity vs temperature as measured on 10/08/04 on twelve samples (full symbols: 0.1 A data, empty symbols: 0.01 A data).

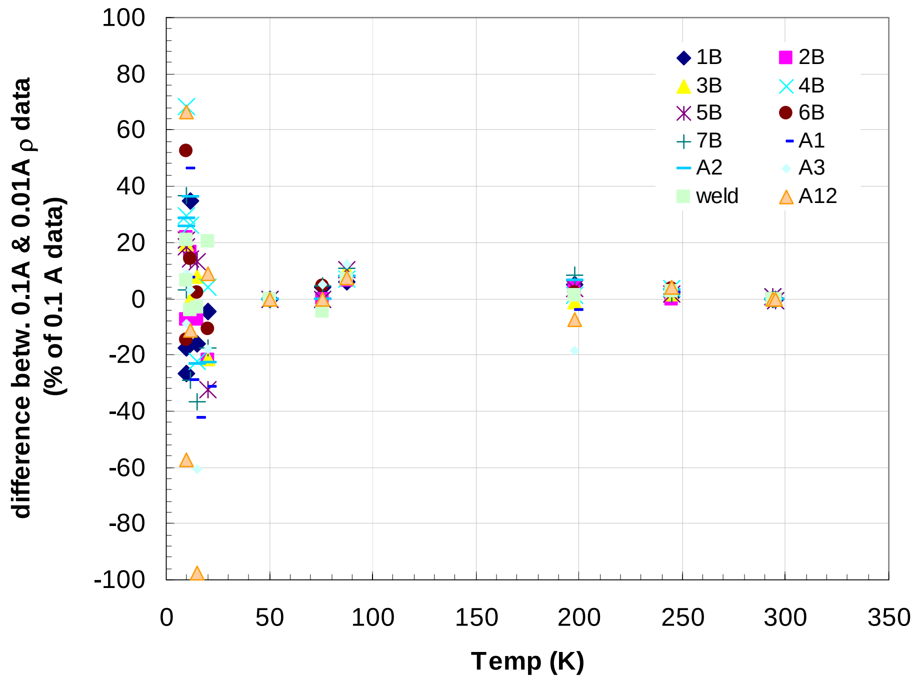

Figure 9: Difference in electrical resistivity between measurements with 0.1 A and 0.01 A currents (in % of the 0.1 A value) for all samples measured on 10/08/2004. The difference could only be compiled in the cases in which the temperatures at which data for both currents were taken were with a few %.

Systematic trends could not be discerned in Figure 9 because of the dominant effect described above. Future studies will hopefully address that. We will, however, choose currents that are larger than 0.01 A, given the limitations found. We nevertheless conclude at this point that non uniform current distributions are not a major concern in our 3R measurements.

6 POLLUTION STUDY

In continuation of a previous study in which it was shown that the RRR could drop significantly if samples are not etched (to remove mechanical defects and surface pollutants due to cutting) prior to the 800C out-gassing bake. Note that the samples were degreased (ultra-sound and detergent) before the heat treatment, so the issue should not be cutting residues or dust, ...etc. This can be an issue of relevance to some external surfaces of cavity parts, for which proper cleaning is sometimes not considered important.

In a variant of such a study an etched sample was submitted to a very high temperature heat treatment at Jefferson Lab[8] (1250C, 24hrs, 10^{-6} Torr). This was done in the context of an effort to grow large grains for magneto-optical measurements at the university of Wisconsin. In fact the RRR dropped strongly again following this high temperature heat treatment, even though the sample had been cleaned and etched before the heat treatment. Also, care was taken to prevent surface contamination during transport by transporting the samples in polyethylene tubes containing dry N_2. In the best case the samples only had an oxide layer on the surface. In this case the drop in RRR must have been caused by the diffusion of oxygen in the bulk. How deeply the bulk had been affected was tested via an additional etching stage in which another 50 μm of material was removed from the surface. This did not change the RRR or bring back the high RRR, indicating that the diffusion had reached deep into the bulk. Note that after the heat treatment 50 μm had already been removed via etching. We conclude from this study that deep diffusion from the surface (presumably of oxygen) during the high temp heat treatment has reduced the RRR throughout the entire bulk. This is consistent with previous observation that indicated that such high temperature heat treatments can only be conducted in the presence of Ti as a getter to prevent the surface to bulk diffusion of the oxide and other surface contaminants.

Table 7: RRR of 3rd harmonic / batch 1 sample as received, after etching and standard heat treatment and after a very high temperature heat treatment. * heat treatment performed at JLab (A.M. Valente); ** Measurement performed at the university of Wisconsin (A. Squitieri). ***Note that the sample that was heat treated at high temperature (#2) was not the same as the sample that was RRR measured as received and after the standard treatment (#1). In fact the RRR value for the as received and standard treated samples were not derived from separate measurements but represent an average derived from the measurements on (similar) samples C1-C5 in **Table 3**.

Sample history	**RRR**	**#**
as received	~410***	1
US degrease, 100μm BCP, UPW rinse, 800C/5hrs (~10^{-6}T), 20μm BCP, UPW rinse, dry N2	~410***	1
Stored in dry N2, 1250C/24hrs(~10^{-6}T)*, dry N2, 50μm BCP, UPW rinse, dry N2	280**	2
50μm BCP, UPW rinse, dry N2	**260**	**2**

[8] Thanks to Anne-Marie Valente from TJNAF for her help.

APPENDIX A

Table 8: Resistance data in Ohm of 3rd harmonic (A1-A6) and CKM (C1-C6) batch 1 samples before treatment. Measurement run 09/22/2003.

Temp (K)	A-1	A-2	A-3	A-4	A-5	A-6	C-1	C-2	C-3	C-4	C-5	C-6
ambient												
294.0765	0.00109	0.0011	0.0011	0.00109	0.00109	0.0011	0.00139	0.00141	0.00138	0.00137	0.00137	0.00137
294.0295	0.00109	0.0011	0.0011	0.00109	0.00109	0.0011	0.00139	0.0014	0.00138	0.00137	0.00137	0.00137
294.1166	0.00109	0.0011	0.0011	0.00109	0.00109	0.0011	0.00139	0.00141	0.00138	0.00137	0.00137	0.00137
293.6888	0.00109	0.0011	0.0011	0.00109	0.00109	0.0011	0.00139	0.00141	0.00138	0.00137	0.00137	0.00137
293.1883	0.00107	0.00109	0.00108	0.00108	0.00108	0.00109	0.00138	0.00139	0.00137	0.00135	0.00135	0.00135
293.3183	0.00108	0.00109	0.00108	0.00108	0.00108	0.00109	0.00138	0.00139	0.00137	0.00135	0.00136	0.00135
293.3614	0.00108	0.00109	0.00108	0.00108	0.00108	0.00109	0.00138	0.00139	0.00137	0.00135	0.00136	0.00135
293.5776	0.00108	0.00109	0.00108	0.00108	0.00108	0.00109	0.00138	0.00139	0.00137	0.00135	0.00136	0.00135
average	0.001083	0.001095	0.00109	0.001085	0.001085	0.001095	0.001385	0.001399	0.001375	0.00136	0.001364	0.00136
low temp												
9.39685	2.73E-06	2.82E-06	2.58E-06	2.78E-06	2.73E-06	2.82E-06	3.65E-06	3.46E-06	3.26E-06	3.26E-06	3.12E-06	3.31E-06
9.39712	2.34E-06	2.43E-06	2.68E-06	2.43E-06	2.43E-06	2.48E-06	3.12E-06	3.31E-06	3.16E-06	3.26E-06	3.36E-06	3.21E-06
average	2.535E-06	2.63E-06	2.63E-06	2.61E-06	2.58E-06	2.65E-06	3.39E-06	3.39E-06	3.21E-06	3.26E-06	3.24E-06	3.26E-06
RRR	**427.5**	**417.1**	**414.4**	**416.5**	**420.5**	**413.2**	**409.2**	**413.2**	**428.3**	**417.2**	**420.9**	**417.2**

Table 9: Dimensions of 3rd harmonic (A1-A6) and CKM (C1-C6) batch 1 samples before treatment.

	A1	A2	A3	A4	A5	A6	C-1	C-2	C-3	C-4	C-5	C-6
Width (mm)	2.58	2.57	2.57	2.58	2.575	2.56	2.56	2.56	2.56	2.57	2.56	2.59
Thick (mm)	2.92	2.93	2.93	2.93	2.94	2.93	2.34	2.34	2.34	2.33	2.34	2.33
dist betw Vtaps (mm)	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6
A/l (m)	0.0001308	0.0001307	0.000131	0.00013	0.00013	0.00013	0.000104	0.000104	0.000104	0.000104	0.000104	0.000105
angle	n	y	y	n	n	y	y	n	n	y	y	n

Table 10: Resistance data in Ohm of 3rd harmonic (A1-A6) and CKM (C1-C6) batch 1 samples after treatment. Measurement run 02/16/2004.

sample	A1	A2	A3	A4	A5	A6	C1	C2	C3	C4	C5	C6
ambient												
284.77707	-0.00107	-0.00108	-0.0011	**-0.00109**	-0.00111	**-0.00109**	-0.00138	-0.00141	-0.00146	-0.00136	-0.00142	-0.00139
284.84644	-0.00107	-0.00108	-0.0011	**-0.00109**	-0.00111	**-0.00109**	-0.00138	-0.00141	-0.00146	-0.00136	-0.00142	-0.00139
284.811755	-0.00107	-0.00108	-0.0011	**-0.00109**	-0.00111	**-0.00109**	-0.00138	-0.00141	-0.00146	-0.00136	-0.00142	-0.00139
289.9125	-0.0011	-0.0011	-0.00112	**-0.00111**	-0.00113	**-0.00111**	-0.00141	-0.00144	-0.00148	-0.00138	-0.00145	-0.00141
variation (%)	-2.784	-1.8	-1.8	-1.8	-1.8	-1.8	-2.2	-2.1	-1.4	-1.5	-2.1	-1.4
low temp												
9.38822	-0.0000026	-0.00000273	-2.9E-06	**-2.9E-06**	-2.5E-06	**-1.9E-06**	-2.9E-06	-3.4E-06	-4.2E-06	-3E-06	-3.4E-06	-3.1E-06
9.38823	-0.00000251	-0.00000251	-2.6E-06	**-3.1E-06**	-2.6E-06	**-2.2E-06**	-2.9E-06	-3.1E-06	-3.9E-06	-3.3E-06	-3.5E-06	-3.1E-06
9.38857	-0.00000264	-0.00000287	-2.7E-06	**-2.7E-06**	-2.8E-06	**-2.5E-06**	-3.2E-06	-3E-06	-3.6E-06	-3.3E-06	-3.1E-06	-3.1E-06
9.38834	-2.583E-06	-2.703E-06	-2.8E-06	**-2.9E-06**	-2.6E-06	**-2.2E-06**	-3E-06	-3.2E-06	-3.9E-06	-3.2E-06	-3.3E-06	-3.1E-06

variation (%)	-5.03	-13.3	-9.8	-12.5	-10.3	**-24.3**	-9	-13.8	-13.6	-9.7	-10.8	-1.3
RRR (after treatment)	**414.2**	**399.5**	**398.6**	**379.8**	**424.7**	**500**	**460**	**445.3**	**376.3**	**425.9**	**428.6**	**453.8**

Table 11: Dimensions of 3rd harmonic (1-6) and CKM (7-12) batch-1 samples after treatment.

AFTER TREATMENT		etching:	150	microns								
Width (mm)	2.28	2.27	2.27	2.28	2.275	2.26	2.26	2.26	2.26	2.27	2.26	2.29
Thick (mm)	2.62	2.63	2.63	2.63	2.64	2.63	2.04	2.04	2.04	2.03	2.04	2.03
dist betw Vtaps (mm)	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6
angle	n	y	y	n	n	y	y	n	n	y	y	n
A/l (m)	0.0001152	0.0001152	0.000115	0.00012	0.00012	0.00011	8.894E-05	8.89E-05	8.89E-05	8.89E-05	8.894E-05	8.97E-05

APPENDIX B

Table 12: Resistance data in Ohm of 3rd harmonic weld-series 1. Measurement run 04/10/2004.

	BW 1	**BW 2**	**BW 3**	**BW 4**	**W0 A8**	**W+1A9**	**W+2A10**	**W+3A11**	**W-1A7**	**W-2A6**	W-3 A5	W-4 A4
ambient											S11 remeas	S12 remeas
292.0579	0.001	0.00101	0.00097	0.00103	0.00082	0.00085	0.00122	0.00115	0.00102	0.00101	0.00101	0.00101
291.9992	0.001	0.00101	0.00097	0.00102	0.00082	0.00085	0.00122	0.00115	0.00102	0.00101	0.00101	0.00102
289.2383	0.00099	0.00099	0.00096	0.00101	0.00082	0.00085	0.0012	0.00114	0.00101	0.001	0.00105	0.00105
289.1836	0.00099	0.00099	0.00096	0.00101	0.00082	0.00085	0.0012	0.00114	0.00101	0.001	0.00105	0.00106
average	0.000995	0.001	0.000965	0.0010175	0.00082	0.00085	0.00121	0.001145	0.001015	0.001005	0.00103	0.001035
low temp												
9.39283	2.23E-06	0.00000223	0.00000197	0.00000237	0.00000223	0.00000201	0.00000286	0.00000255	0.00000241	2.19E-06	0.00000256	0.00000256
9.39336	1.92E-06	0.00000206	0.00000223	0.00000232	0.00000188	0.00000188	0.00000277	0.00000255	0.00000232	2.19E-06	0.00000251	0.00000226
9.59525	0.0000025	0.00000255	0.00000241	0.00000246	0.00000188	0.00000206	0.00000281	0.00000268	0.00000228	2.32E-06	0.00000272	0.00000277
9.59481	2.46E-06	0.00000259	0.00000237	0.00000241	0.00000219	0.00000201	0.00000299	0.00000286	0.00000237	2.41E-06	0.00000266	0.00000266
9.99508	2.59E-06	0.00000246	0.00000246	0.00000268	0.00000214	0.0000021	0.00000299	0.00000286	0.00000246	2.37E-06	0.00000272	0.00000277
9.99514	0.0000025	0.00000246	0.00000237	0.00000264	0.00000206	0.00000174	0.00000259	0.00000255	0.00000237	2.32E-06	0.00000266	0.00000266
average	2.367E-06	2.39167E-06	2.30167E-06	0.00000248	2.06333E-06	1.96667E-06	0.000002835	0.000002675	2.36833E-06	0.0000023	2.63833E-06	2.61333E-06
RRR	**420.4**	**418.1**	**419.3**	**410.3**	**397.4**	**432.2**	**426.8**	**428.0**	**428.6**	**436.9**	390.4	396.0

Table 13: Dimensions of samples of 3rd harmonic weld-series 1, measured on 04/10/2004.

	BW 1	**BW 2**	**BW 3**	**BW 4**	**W0 A8**	**W+1A9**	**W+2A10**	**W+3A11**	**W-1A7**	**W-2A6**	**W-3A5**	**W-4A4**
Width (mm)	2.5	2.485	2.56	2.44	2.94	2.95	2.025	2.23	2.485	2.49	2.485	2.47
Thick (mm)	2.96	2.97	2.965	2.95	3.25	2.99	2.955	2.96	3	2.97	2.96	2.95
dist btw Vtaps	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6
A/l (m)	0.0001285	0.0001281	0.000132	0.00012	0.00017	0.00015	0.0001039	0.000115	0.000129	0.000128	0.0001277	0.000127
angle	**n**	**y**	**y**	**n**	**n**	**y**	**y**	**n**	**n**	**y**	**y**	**n**

Table 14: Resistance (Ω) and 3R data of 3rd harmonic weld-series 2. Measurement run 05/06/2004.

Temp (K)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
ambient										
292.5176	0.00125	0.00103	0.00108	0.00128	0.0013	0.00129	0.00131	0.0013	0.00129	0.00126
292.6175	0.00125	0.00103	0.00108	0.00128	0.0013	0.00129	0.00131	0.0013	0.00129	0.00126
292.6541	0.00126	0.00103	0.00109	0.00129	0.00131	0.00129	0.00131	0.0013	0.0013	0.00127
292.7833	0.00126	0.00105	0.00108	0.00129	0.00131	0.0013	0.00132	0.00131	0.0013	0.00127
average	0.001255	0.001035	0.0010825	0.001285	0.001305	0.0012925	0.0013125	0.0013025	0.001295	0.001265
low temp										
9.40578	3.22E-06	0.00000261	0.00000251	0.00000322	0.00000322	0.00000307	0.00000322	0.00000307	0.00000312	2.82E-06
9.40445	2.56E-06	0.00000201	0.00000272	0.00000292	0.00000282	0.00000282	0.00000266	0.00000246	0.00000287	2.87E-06
9.59929	3.02E-06	0.00000261	0.00000267	0.00000302	0.00000317	0.00000312	0.00000322	0.00000292	0.00000307	3.07E-06
9.60076	2.56E-06	0.00000191	0.00000246	0.00000312	0.00000287	0.00000287	0.00000287	0.00000271	0.00000302	2.77E-06
10.0086	2.97E-06	0.00000246	0.00000267	0.00000312	0.00000332	0.00000317	0.00000332	0.00000337	0.00000322	2.97E-06

10.00783	2.97E-06	0.00000241	0.00000246	0.00000327	0.00000302	0.00000312	0.00000317	0.00000307	0.00000322	3.02E-06
average	2.883E-06	0.000002335	2.58167E-06	3.1117E-06	0.00000307	3.02833E-06	3.07667E-06	2.93333E-06	3.08667E-06	2.92E-06
RRR	**435.3**	**443.3**	**419.3**	**412.9**	**425.1**	**426.8**	**426.6**	**444.0**	**419.5**	**433.2**

Table 15: Dimensions of samples of 3rd harmonic weld-series 2.

	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
Width (mm)	2.225	2.57	2.625	2.2	2.2	2.213	2.175	2.24	2.21	2.23
Thick (mm)	3.02	3.23	2.98	2.933	2.94	2.934	2.93	2.94	2.935	2.955
dist btw Vtaps	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6
A/l (m)	0.0001167	0.0001441	0.000136	0.00011	0.00011	0.00011	0.0001106	0.000114	0.000113	0.000114
angle	n	y	y	n	n	y	y	n	n	y

Table 16: Resistance (Ω) and 3R data of remaining samples of the 3rd harmonic weld-series 1&2 (weld series 1 samples A1-A3, weld and A12, weld-series 2 samples B1-B7). Measurement run 10/08/2004 (0.1 A data).

Temp (K)	1B	2B	3B	4B	5B	6B	7B	A1	A2	A3	weld	A12
293.5401	0.00147	0.00131	0.00127	0.00128	0.00128	0.00128	0.00127	0.00117	0.00116	0.00116	0.0013	0.00128
293.5503	0.00147	0.00131	0.00127	0.00127	0.00127	0.00128	0.00127	0.00117	0.00116	0.00116	0.0013	0.00128
294.0735	0.00147	0.00131	0.00128	0.00128	0.00128	0.00128	0.00127	0.00117	0.00116	0.00116	0.0013	0.00128
294.0737	0.00147	0.00131	0.00128	0.00128	0.00128	0.00128	0.00127	0.00117	0.00116	0.00116	0.00131	0.00128
294.9817	0.00148	0.00132	0.00128	0.00128	0.00128	0.00129	0.00128	0.00118	0.00117	0.00116	0.00131	0.00129
295.0893	0.00148	0.00132	0.00128	0.00129	0.00129	0.00129	0.00128	0.00118	0.00117	0.00116	0.00131	0.00129
average	0.0014733	0.001313333	0.001276667	0.00128	0.00128	0.001283333	0.001273333	0.001173333	0.001163333	0.00116	0.001305	0.001283333
9.60993	3.42E-06	0.00000322	0.00000317	0.00000286	0.00000307	0.00000307	0.00000312	0.00000281	0.00000281	2.76E-06	0.00000317	0.00000302
9.99286	3.57E-06	0.00000327	0.00000312	0.00000317	0.00000317	0.00000317	0.00000317	0.00000271	0.00000271	2.76E-06	0.00000322	0.00000287
11.99076	3.87E-06	0.00000362	0.00000352	0.00000342	0.00000352	0.00000352	0.00000352	0.00000312	0.00000317	3.12E-06	0.00000387	0.00000362
9.39785	3.32E-06	0.00000302	0.00000292	0.00000302	0.00000307	0.00000302	0.00000302	0.00000266	0.00000261	2.71E-06	0.00000307	0.00000312
average	3.545E-06	3.2825E-06	3.1825E-06	3.1175E-06	3.2075E-06	0.000003195	3.2075E-06	0.000002825	0.000002825	2.838E-06	3.3325E-06	3.1575E-06
RRR	415.60884	400.1015486	401.1521341	410.585405	399.0646921	401.6692749	396.9862302	415.339233	411.79941	408.81057	391.5978995	406.4396939

Table 17: Dimensions of remaining samples of 3rd harmonic weld-series 1&2 measured on 08/10/04.

	1B	2B	3B	4B	5B	6B	7B	A1	A2	A3	weld	A12
Width (mm)	1.84	2.2	2.21	2.2	2.21	2.21	2.21	2.485	2.48	2.45	2.215	2.24
Thick (mm)	2.95	3.23	2.95	2.95	2.95	2.96	2.985	2.94	2.95	2.935	3.02	2.965
dist btw Vtaps	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6	57.6
A/l (m)	9.424E-05	0.0001234	0.000113	0.00011	0.00011	0.00011	0.0001145	0.000127	0.000127	0.000125	0.0001161	0.000115
angle	n	y	y	n	n	y	y	n	n	y	y	n